A TEXT-BOOK

OF

GENERAL ASTRONOMY

FOR

COLLEGES AND SCIENTIFIC SCHOOLS

BY

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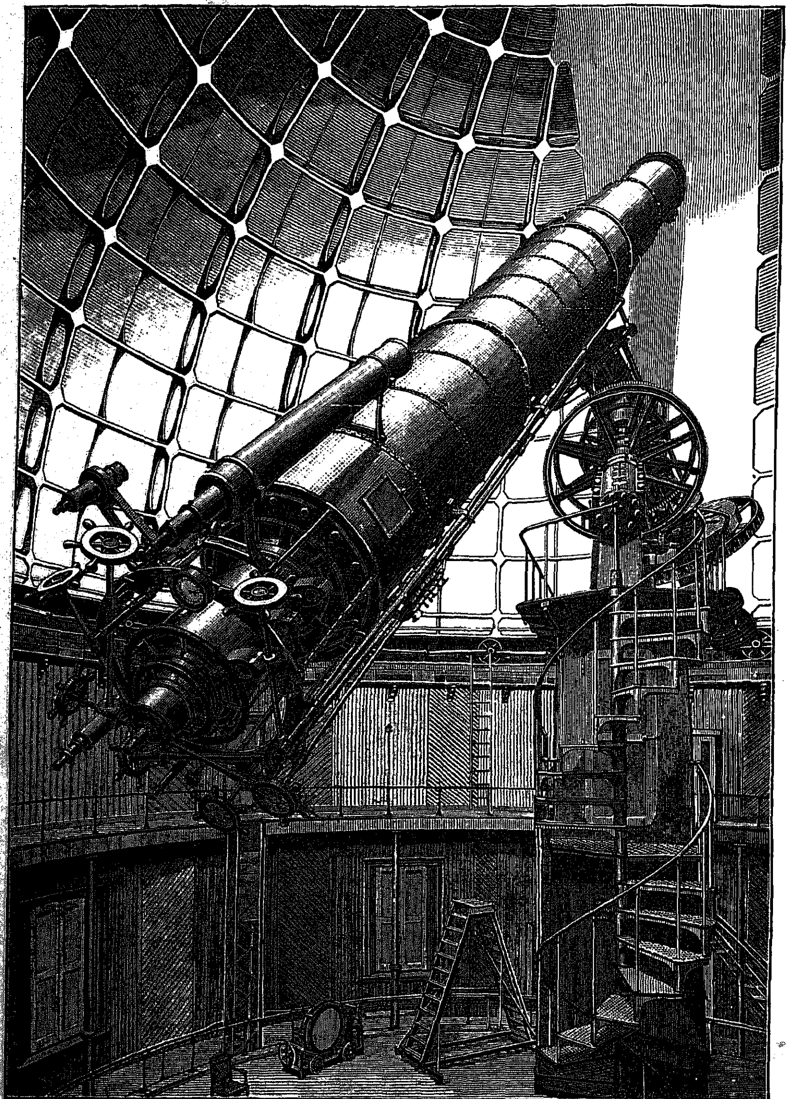
REVISED EDITION

GINN & COMPANY
BOSTON · NEW YORK · CHICAGO · LONDON



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PREFACE TO FIRST EDITION.

The present work is designed as a text-book of Astronomy suited to the *general* course in our colleges and schools of science, and is meant to supply that amount of information upon the subject which may fairly be expected of every "liberally educated" person. While it assumes the previous discipline and mental maturity usually corresponding to the latter years of the college course, it does not demand the peculiar mathematical training and aptitude necessary as the basis of a *special* course in the science — only the most elementary knowledge of Algebra, Geometry, and Trigonometry is required for its reading. Its aim is to give a clear, accurate, and justly proportioned presentation of astronomical facts, principles, and methods in such a form that they can be easily apprehended by the average college student with a reasonable amount of effort.

The limitations of time are such in our college course that probably it will not be possible in most cases for a class to take thoroughly everything in the book. The fine print is to be regarded rather as collateral reading, important to a complete view of the subject, but not essential to the course. Some of the chapters can even be omitted in cases where it is found necessary to abridge the course as much as possible; *e.g.*, the chapters on Instruments and on Perturbations.

While the work is no mere compilation, it makes no claims to special originality: information and help have been drawn from all available sources. The author is under great obligations to the astronomical histories of Grant and Wolf, and especially to Miss Clerke's admirable "History of Astronomy in the Nineteenth Century." Many data also have been drawn from Houzeau's valuable "Vade Mecum de l'Astronome."

It has been intended to bring the book well down to date, and to indicate to the student the sources of information on subjects which are necessarily here treated inadequately on account of the limitations of time and space.

Special acknowledgments are due to Professor Langley and to his publishers, Messrs. Ticknor & Co., for the use of a number of illustrations from his beautiful book, "The New Astronomy"; and also to D. Appleton & Co. for the use of several cuts from the author's little book on the Sun. Professor Trowbridge of Cambridge kindly provided the original negative from which was made the cut illustrating the comparison of the spectrum of iron with that of the sun. Warner & Swasey of Cleveland and Fauth & Co. of Washington have also furnished the engravings of a number of astronomical instruments.

Professors Todd, Emerson, Upton, and McNeill have given most valuable assistance and suggestions in the revision of the proof; as indeed, in hardly a less degree, have several others.

PRINCETON, N. J., August, 1888.

PREFACE TO THE REVISED EDITION.

THE progress of Astronomy has been very rapid since the first publication of this book in 1889, and, although in the meantime the author has attempted as far as possible to keep the successive issues "up to date" by minor changes, notes, and "addenda," it has at last become imperative to give the work a thorough revision, rewriting certain portions and making considerable additions, in order to embody the new and important results which have been obtained during the last ten years.

The Appendix has also been enlarged by several articles giving the demonstration of certain fundamental methods and

formulæ for which, in previous editions, the student was referred to other works not always conveniently accessible. In one or two of these articles the Calculus is necessarily used.

The various tables have been corrected to correspond with the latest and most authoritative data; and a set of illustrative exercises has been added at the end of nearly every chapter.

While the book has thus been necessarily somewhat increased in size, the changes have been so managed that no serious difficulty will be encountered in using the new edition along with the older issues. The original numbering of the *articles* has been retained throughout, with only one or two exceptions, the interpolated matter being designated by numbers with asterisks.

It is believed that the book, so far as its scope extends, may now be taken as fairly representing the present state of the science, although some of the most important recent discoveries are hardly made so prominent as would have been the case if the revision had not been substantially completed and prepared for the press more than two years ago; the actual printing having been much delayed by various causes.

Special acknowledgments are due from the author to the publishers for the liberality with which they have made the extensive and expensive changes in the plates, and to Appleton & Co., and Professors Frost, Hale, Holden, and Pickering for many of the new illustrations.

PRINCETON UNIVERSITY, March, 1898.

PREFACE TO ISSUE OF 1904.

IN this issue of the Revised Edition a considerable number of corrections, changes, and additions have been made in the text, and three Addenda have been appended, in order to bring the book up to date as far as possible.

AUGUST, 1904.

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INTRODUCTION.

1. ASTRONOMY (ἄστρον νόμος) is the science which treats of the heavenly bodies. As such bodies we reckon the sun and moon, the planets (of which the earth is one) and their satellites, comets and meteors, and finally the stars and nebulæ.

We have to consider in Astronomy: —

(*a*) The motions of these bodies, both real and apparent, and the laws which govern these motions.

(*b*) Their forms, dimensions, and masses.

(*c*) Their nature, constitution, and conditions.

(*d*) The effects they produce upon each other by their attractions, radiations, or by any other ascertainable influence.

It was an early, and has been a most persistent, belief that the heavenly bodies have a powerful influence upon human affairs, so that from a knowledge of their positions and "aspects" at critical moments (as for instance at the time of a person's birth) one could draw up a "horoscope" which would indicate the probable future.

The *pseudo-science* which was founded on this belief was named Astrology, — the elder sister of Alchemy, — and for centuries Astronomy was its handmaid; *i.e.*, astronomical observations and calculations were made mainly in order to supply astrological data.

At present the end and object of astronomical study is chiefly knowledge pure and simple; so far as now appears, its development has less direct bearing upon the material interests of mankind than that of any other of the natural sciences. It is not likely that great inventions and new arts will grow out of its laws and principles, such as are continually arising from physical, chemical, and biological discoveries, though of course it would be rash to say that such outgrowths are impossible. But the student of Astronomy must expect his chief profit to be intellectual, in the widening of the range of thought and conception, in the pleasure attending the discovery of simple law working out the most complicated results, in the delight

over the beauty and order revealed by the telescope in systems otherwise invisible, in the recognition of the essential unity of the material universe, and of the kinship between his own mind and the infinite Reason that formed all things and is immanent in them.

At the same time it should be said at once that, even from the lowest point of view, Astronomy is far from a useless science. The *art of navigation* depends for its very possibility upon astronomical prediction. Take away from mankind their almanacs, sextants, and chronometers, and commerce by sea would practically stop. The science also has important applications in the survey of extended regions of country, and the establishment of boundaries, to say nothing of the accurate determination of time and the arrangement of the calendar.

It need hardly be said that Astronomy is not separated from kindred sciences by sharp boundaries. It would be impossible, for instance, to draw a line between Astronomy on one side and Geology and Physical Geography on the other. Many problems relating to the formation and constitution of the earth belong alike to all three.

2. Astronomy is divided into many branches, some of which, as ordinarily recognized, are the following: —

1. **Descriptive Astronomy.** — This, as its name implies, is merely an orderly statement of astronomical facts and principles.

2. **Practical Astronomy.** — This is quite as much an art as a science, and treats of the instruments, the methods of observation, and the processes of calculation by which astronomical facts are ascertained.

3. **Theoretical Astronomy,** which treats of the calculations of orbits and ephemerides, including the effects of so-called "perturbations."

4. **Mechanical Astronomy,** which is simply the application of mechanical principles to explain astronomical facts (chiefly the planetary and lunar motions). It is sometimes called *Gravitational* Astronomy, because, with few exceptions, gravitation is the only force sensibly concerned in the motions of the heavenly bodies. Until within thirty years this branch of the science was generally designated as *Physical Astronomy*, but the term is now objectionable because of late it has been used by many writers to denote a very different and comparatively new branch of the science; viz., —

6. **Spherical Astronomy.** — This, discarding all consideration of absolute dimensions and distances, treats the heavenly bodies simply as objects moving on the "surface of the celestial sphere": it has to do only with angles and directions, and, strictly regarded, is in fact merely Spherical Trigonometry applied to Astronomy.

3. The above-named branches are not distinct and separate, but they overlap in all directions. Spherical Astronomy, for instance, finds the demonstration of many of its formulæ in Gravitational Astronomy, and their application appears in Theoretical and Practical Astronomy. But valuable works exist bearing all the different titles indicated above, and it is important for the student to know what subjects he may expect to find discussed in each; for this reason it has seemed worth while to name and define the several branches, although they do not distribute the science between them in any strictly logical and mutually exclusive manner.

In the present text-book little regard will be paid to these subdivisions, since the object of the work is not to present a complete and profound discussion of the subject such as would be demanded by a professional astronomer, but only to give so much knowledge of the facts and such an understanding of the principles of the science as may fairly claim to be elements in a liberal education. If this result is gained in the reader's case, it may easily happen that he will wish for more than he can find in these pages, and then he must have recourse to works of a higher order and far more difficult, dealing with the subject more in detail and more thoroughly.

To master the present book no further preparation is necessary than a very elementary knowledge of Algebra, Geometry, and Trigonometry, and a similar acquaintance with Mechanics and Physics, especially Optics. While nothing short of high mathematical attainments will enable one to become eminent in the science, yet a perfect comprehension of all its fundamental methods and principles, and a very satisfactory acquaintance with its main results, is quite within the reach of every person of ordinary intelligence, without any more extensive training than may be had in

our common schools. At the same time the necessary statements and demonstrations are so much facilitated by the use of trigonometrical terms and processes that it would be unwise to dispense with them entirely in a work to be used by pupils who have already become acquainted with them.

In discussing the different subjects which present themselves, the writer will adopt whatever plan appears best fitted to convey to the student clear and definite ideas, and to impress them upon the mind. Usually it will be best to proceed in the Euclidean order, by first stating the fact or principle in question, and then explaining its demonstration. But in some cases the inverse process is preferable, and the conclusion to be reached will appear gradually unfolding itself as the result of the observations upon which it depends, just as its discovery came about.

The occasional references to "Physics" refer to the "Elementary Text-Book of Physics," by Anthony and Brackett; Magie's revised edition, 1897. John Wiley & Sons, N.Y.

CHAPTER I.

THE "DOCTRINE OF THE SPHERE," DEFINITIONS, AND GENERAL CONSIDERATIONS.

ASTRONOMY, like all the other sciences, has a terminology of its own, and uses technical terms in the description of its facts and phenomena. In a popular essay it would of course be proper to avoid such terms as far as possible, even at the expense of circumlocutions and occasional ambiguity; but in a text-book it is desirable that the reader should be introduced to the most important of them at the very outset, and made sufficiently familiar with them to use them intelligently and accurately.

4. The Celestial Sphere. To an observer looking up to the heavens at night it seems as if the stars were glittering points attached to the inner surface of a dome; since we have no direct perception of their distance there is no reason to imagine some nearer than others, and so we involuntarily think of the surface as *spherical* with ourselves in its centre. Or if we sometimes feel that the stars and other objects in the sky really differ in distance, we still instinctively imagine an immense sphere surrounding and enclosing all. Upon this sphere we imagine lines and circles traced, resembling more or less the meridians and parallels upon the surface of the earth, and by reference to these circles we are able to describe intelligently the apparent positions and motions of the heavenly bodies.

This celestial sphere may be regarded in either of two different ways, both of which are correct and lead to identical results.

(*a*) We may imagine it, in the first place, as transparent, and of merely finite (though undetermined) dimensions, *but in some way so attached to, and connected with, the observer that his eye always remains at its centre wherever he goes.* Each observer, in this way of viewing it, carries his own sky with him, and is the centre of his own heavens.

(*b*) Or, in the second place, — and this is generally the more convenient way of regarding the matter, — we may consider the celestial

sphere as mathematically *infinite* in its dimensions: then, let the observer go where he will, he cannot sensibly get away from its centre. Its radius being "greater than any assignable quantity," the size of continents, the diameter of the earth, the distance of the sun, the orbits of planets and comets, even the spaces between the stars, are all insignificant, and the whole visible universe shrinks *relatively* to a mere point at its centre. In what follows we shall use this conception of the celestial sphere.[1]

The apparent place of any celestial body will then be the point on the celestial sphere where the line drawn from the eye of the observer in the direction in which he sees the object, and produced indefinitely, pierces the sphere. Thus, in Figure 1, *A*, *B*, *C* are the apparent places of *a*, *b*, and *c*, the observer being at *O*. The apparent place of a heavenly body evidently depends solely upon its *direction*, and is wholly independent of its *distance* from the observer.

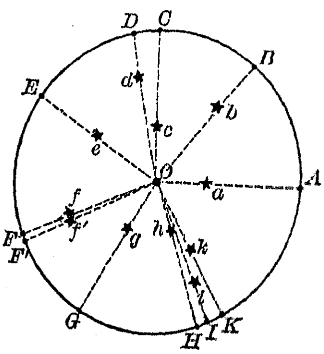

FIG. 1.

5. Linear and Angular Dimensions. — Linear dimensions are such as may be expressed in *linear units*; *i.e.*, in miles, feet, or inches; in metres or millimetres. Angular dimensions are expressed in *angular units*; *i.e.*, in right angles, in radians,[2] or (more commonly in astronomy) in degrees, minutes, and seconds. Thus, for instance, the *linear* semi-

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[1] To most persons the sky appears, not a true hemisphere, but a *flattened* vault, as if the horizon were more remote than the zenith. This is a subjective effect due mainly to the intervening objects between us and the horizon. The sun and moon when rising or setting look much larger than when they are higher up, for the same reason.

[2] *A radian* is the angle which is measured by an arc equal in length to radius. Since a circle whose radius is unity has a circumference of 2π, and contains $360°$, or $21{,}600'$, or $1{,}296{,}000''$, it follows that a *radian* contains $\left(\frac{360}{2\pi}\right)°$, or $\left(\frac{21600}{2\pi}\right)'$, or $\left(\frac{1296000}{2\pi}\right)''$; *i.e.* (approximately), a radian $= 57.3° = 3437.7' = 206264.8''$.

Hence, to reduce to seconds of arc an angle expressed in radians, we must multiply it by the number 206264.8; a relation of which we shall have to make frequent use.

diameter of the sun is about 697,000 kilometres (433,000 miles), while its *angular* semidiameter is about 16′, or a little more than a quarter of a degree. Obviously, angular units alone can properly be used in describing apparent distances and dimensions in the sky. For instance, one cannot say correctly that the two stars which are known as "the pointers" are two or five or ten *feet* apart: their distance is about five *degrees*.

It is sometimes convenient to speak of "*angular area*," the unit of which is a "square degree" or a "square minute"; *i.e.*, a small square in the sky of which each side is 1° or 1′. Thus we may compare the angular area of the constellation Orion with that of Taurus, in *square degrees*, just as we might compare Pennsylvania and New Jersey in square miles.

6. Relation between the Distance and Apparent Size of an Object. —Suppose a globe having a radius BC equal to r. As seen from

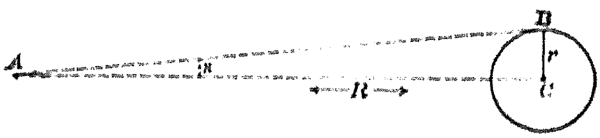

FIG. 2.

the point A (Fig. 2) its apparent (*i.e.*, *angular*) semidiameter will be BAC or s, its distance being AC or R.

We have immediately from Trigonometry, since B is a right angle,

$$\sin s = \frac{r}{R}.$$

If, as is usual in Astronomy, the diameter of the object is small as compared with its distance, we may write $s = \frac{r}{R}$, which gives s in *radians* (not in degrees or seconds). If we wish it in the ordinary angular units,

$$s^\circ = 57.3\frac{r}{R}, \text{ or } s' = 3437.7\frac{r}{R}, \text{ or } s'' = 206264.8\frac{r}{R},$$

where s° means s in *degrees*; s', s in *minutes*; s'', s in *seconds* of arc. In either form of the equation we see that the apparent diameter *varies directly as the linear diameter, and inversely as the distance.*

In the case of the moon, $R =$ about 239,000 miles; and r, 1081 miles. Hence $s = \frac{1081}{239000} = \frac{1}{221}$ of a radian, which is a little more than $\frac{1}{4}$ of a degree, or about 933″.

It may be mentioned here as a rather curious fact that most persons say that the moon appears about *a foot in diameter*; at least, this seems to be the average estimate.[1] This implies that the surface of the sky appears to them only about 110 feet away, since that is the distance at which a disc one foot in diameter would have an angular diameter of $\frac{1}{110}$ of a radian, or $\frac{1}{2}$°.

7. Vanishing Point. — Any system of parallel lines produced in one direction will *appear* to pierce the celestial sphere at a single point. They actually pierce it at different points, separated on the surface of the sphere by linear distances equal to the actual distances between the lines, but on the infinitely distant surface these linear distances, being only finite, become invisible, subtending at the centre angles less than anything assignable. The different points, therefore, coalesce into a *spot* of apparently infinitesimal size — the so-called "vanishing point" of perspective. Thus the axis of the earth and *all lines parallel to this axis* point to the celestial pole.

POINTS AND CIRCLES OF REFERENCE.

8. The Zenith. — The Zenith is the *point vertically overhead*, i.e., the point where a plumb-line, produced upwards, would pierce the sky: it is determined by the *direction of gravity* where the observer stands.

If the earth were exactly spherical, the zenith might also be defined as the point where a line drawn *from the centre of the earth upward through the observer* meets the sky. But since, as we shall see hereafter, the earth is not an exact globe, this second definition indicates a point known as the *Geocentric Zenith*, which is not identical with the *True* or *Astronomical Zenith*, determined by the direction of gravity.

9. The Nadir. — The Nadir is the point opposite the zenith under foot, of course.

Both zenith and nadir are derived from the Arabic, which language has also given us many other astronomical terms.

[1] See note on p. 20, at the end of the chapter.

10. Horizon. — The Horīzon[1] is a great circle of the celestial sphere, having the zenith and nadir as its poles: it is therefore half-way between them, and 90° from each.

A *horizontal plane*, or the *plane of the horizon*, is a plane perpendicular to the direction of gravity, and the horizon may also be correctly defined as the intersection of the celestial sphere by this plane.

Many writers make a distinction between the *sensible* and *rational* horizons. The plane of the sensible horizon passes through the observer; the plane of the rational horizon passes through the centre of the earth, parallel to the plane of the sensible horizon: these two planes, parallel to each other, and everywhere about 4000 miles apart, trace out on the sky the two horizons, the sensible and the rational. It is evident, however, that on the infinitely distant surface of the celestial sphere, the two traces sensibly coalesce into one single great circle, which is the horizon as first defined. We get, therefore, but one *horizon circle* in the sky.

11. The Visible Horizon is the line where sky and earth meet. On land it is an irregular line, broken by hills and trees, and of no astronomical value; but at sea it is a true circle, and of great importance in observation. It is not, however, a *great* circle, but, technically speaking, only a *small* circle; depressed below the true horizon by an amount depending upon the observer's elevation above the water. This depression is called the *Dip of the Horizon*, and will be discussed further on.

12. Vertical Circles. — These are great circles passing through the zenith and nadir, and therefore necessarily perpendicular to the horizon — *secondaries* to it, to use the technical term.

Parallels of Altitude, or Almucantars. — These are small circles parallel to the horizon: the term Almucantar is seldom used.

The points and circles thus far defined are determined entirely by the *direction of gravity* at the station occupied by the observer.

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13. The Diurnal Rotation of the Heavens. — If one watches the sky for a few hours some night, he will find that, while certain stars rise in the east, others set in the west, and nearly all the constellations change their places. Watching longer and more closely, it will

[1] Beware of the common, but vulgar, pronunciation, *Hórĭzon.*

sphere — the point about which it turns — is in the north, not quite half-way up from the horizon to the zenith, for in that region the stars hardly move at all, but keep their places all night long.

14. The Poles. — The Poles may be defined as the two points in the sky, one in the northern hemisphere and one in the southern,

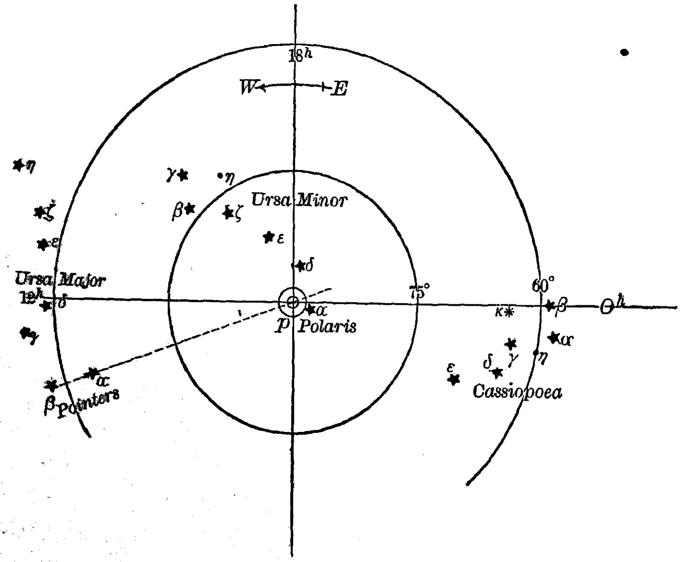

FIG. 3.—The Pole Star and the Pointers.

where a *star's diurnal circle reduces to zero ; i.e.*, points where, if a star were placed, it would suffer no apparent change of place during the whole twenty-four hours. The line joining these poles is, of course, the *axis* of the celestial sphere, about which it seems to rotate daily.

The exact place of the pole may be found by observing some star very near the pole at two times 12 hours apart, and taking the middle point between the two observed places of the star.

The definition of the pole just given is independent of any theory as to the cause of the apparent rotation of the heavens. If, how-

ever, we admit that it is due to the earth's rotation on its axis, then we may define the poles as the *points where the earth's axis produced pierces the celestial sphere.*

15. The Pole-star (Polaris). — The place of the northern pole is very conveniently marked by the *Pole-star*, a star of the second magnitude, which is now only about $1\frac{1}{4}°$ from the pole: we say *now*, because on account of a slow change in the direction of the earth's axis, called "precession" (to be discussed later), the distance between the pole-star and the pole is constantly changing, and has been for several centuries gradually decreasing.

The pole-star stands comparatively solitary in the sky, and may easily be recognized by means of the so-called "pointers," — two stars in the "dipper" (in the constellation of Ursa Major) — which point very nearly to it, as shown in Fig. 3. The pole is very nearly on the line joining Polaris with the star Mizar (ζ Urs. Maj., at the bend in the handle of the dipper), and at a distance just about one-quarter of the distance between the pointers, which are nearly 5° apart.

The southern pole, unfortunately, is not so marked by any conspicuous star.

16. The Celestial Equator, or Equinoctial Circle. — This is a great circle midway between the two poles, and of course 90° from each. It may also be defined as the intersection of the plane of the earth's equator with the celestial sphere. It derives its name from the fact that, at the two dates in the year when the sun crosses this circle — about March 20 and Sept. 22 — the day and night are equal in length.

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17. The Vernal Equinox, or First of Aries. — The Equinox, strictly speaking, is the *time when* the sun crosses the equator, but the term has come by accommodation to denote also the *point where* it crosses. This crossing occurs twice a year, about March 20th and September 22d, and the *Vernal Equinox is the point on the equator where the sun crosses it in the spring.* It is sometimes called the *Greenwich of the Celestial Sphere,* because it is used as a reference point in the sky, much as Greenwich is on the earth. Its position is not marked by any conspicuous star.

Why this point is also called the "First of Aries" will appear later, when we come to speak of the zodiac and its "signs."

to the celestial equator. They correspond exactly to the meridians of the earth, and some writers call them "Celestial Meridians"; but the term is objectionable, as likely to lead to confusion with *the* Meridian, to be noted immediately.

19. The Meridian and Prime Vertical. — *The Meridian is the great circle passing through the pole and the zenith.* Since it is a great circle, it must necessarily pass through *both* poles, and through the nadir as well as the zenith, and must be perpendicular both to the equator and to the horizon.

It may also be correctly defined as the *Vertical Circle* which passes through the *pole;* or, again, as the *Hour-Circle* which passes through the *zenith*, since all vertical circles must pass through the zenith, and all hour-circles through the pole.

The Prime Vertical is the Vertical Circle (passing through the zenith) at right angles to the meridian; hence lying *east and west* on the celestial sphere.

20. The Cardinal Points. — The North and South Points are the points on the horizon where it is intersected by the meridian; the East and West Points are where it is cut by the prime vertical, and also by the equator. The North *Point*, which is on the horizon, must not be confounded with the North *Pole*, which is not on the horizon, but at an elevation equal (see Art. 30) to the latitude of the observer.

With these circles and points of reference we have now the means to describe intelligibly the position of a heavenly body, in several different ways.

We may give its *altitude* and *azimuth*, or its *declination* and *hour-angle;* or, if we know the time, its *declination* and *right ascension.* Either of these pairs of co-ordinates, as they are called, will define its place in the sky.

21. Altitude and Zenith Distance (Fig. 4). — The Altitude of a heavenly body is *its angular elevation above the horizon*, and is measured by the arc of the vertical circle passing through the body, and intercepted between it and the horizon.

meaning as the *true bearing* in surveying and navigation.

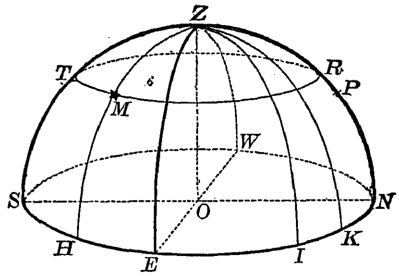

FIG. 4. — The Horizon and Vertical Circles.

O, the place of the Observer.
OZ, the Observer's Vertical.
Z, the Zenith; *P*, the Pole.
SENW, the Horizon.
SZPN, the Meridian.
EZW, the Prime Vertical.

M, some Star.
ZMH, arc of the Star's Vertical Circle.
TMR, the Star's Almucantar.
Angle *TZM*, or arc *SWNEH*, Star's *Azimuth*.
Arc *HM*, Star's *Altitude*.
Arc *ZM*, Star's *Zenith Distance*.

There are various ways of reckoning azimuth. Many writers express it in the same manner as *the bearing* is expressed in surveying; *i.e.*, so many degrees east or west of north or south; N. 20° E., etc. The more usual way at present is, however, to reckon it in degrees from the south point clear round through the west to the point of beginning: thus an object in the SW. would have an azimuth of 45°; in the NW., 135°; in the N., 180°; in the NE., 225°; and in the SE., 315°. For example, to find a star whose azimuth is 260°, and altitude 60°, we must face N. 80° E., and then look up two-thirds of the way to the zenith. The object in this case has an *amplitude* of 10° N. of E., and a zenith distance of 30°. Evidently both the azimuth and altitude of a heavenly body are continually changing.

The *Amplitude* of a body is the angle intercepted between the Prime vertical and the Vertical circle which passes through the body.

In Fig. 4, *SENW* represents the horizon, *S* being the south point, and *Z* the zenith. The angle *SZM*, which numerically equals the arc *SH*, is the *Azimuth* of the star *M*; while *EZM*, or *EH*, is its *Amplitude*. *MH* is its *Altitude*, and *ZM* its *Zenith Distance*.

23. Declination and Polar Distance (Fig. 5). — The Declination of a heavenly body is its *angular distance north or south of the celestial equator*, and is measured by the arc of the hour-circle passing through the object, intercepted between it and the equator. It is reckoned positive (+) north of the celestial equator, and negative (−) south of it. Evidently it is precisely analogous to the latitude of a place on the earth. The *north-polar distance* of a star is its angular distance from the North Pole, and is simply the complement of the declination. Declination + North-Polar Distance = 90°.

The declination of a star remains always the same; at least, the slow changes that it undergoes need not be considered for our present purpose. "*Parallels of Declination*" are small circles parallel to the celestial equator.

24. The Hour-Angle (Fig. 5). — The Hour-Angle of a star is the *angle at the pole between the meridian and the hour-circle passing through the star.* It may be reckoned in degrees; but it also may be, and most commonly is, reckoned in *hours, minutes, and seconds of time;* the hour being equivalent to fifteen degrees, and the minute and second of time being equal to fifteen minutes and seconds of arc respectively.

Of course the hour-angle of an object is continually changing, being zero when the object is on the meridian, one hour, or fifteen degrees, when it has moved that amount westward, and so on.

25. Right Ascension (Fig. 5). — The Right Ascension of a star is *the angle at the pole between the star's hour-circle and the hour-circle (called the Equinoctial Colure), which passes through the vernal equinox.*

It may be defined also as the arc of the equator, intercepted between the vernal equinox and the foot of the star's hour-circle.

It is always reckoned from the equinox *toward the east;* sometimes in degrees, but usually in *hours, minutes, and seconds of time. The right ascension, like the declination, remains unchanged by the diurnal motion.*

26. Sidereal Time (Fig. 5). For many astronomical purposes it is convenient to reckon time, not by the sun's position in the sky, but by that of the vernal equinox.

The Sidereal Time at any moment may be defined as *the hour angle of the vernal equinox*. It is sidereal *noon*, when the equinoctial point is on the meridian; 1 o'clock (sidereal) when its hour angle is 15°; and 23 o'clock when its hour angle is 345°, *i.e.*, when the vernal equinox is an hour *east* of the meridian; the time being reckoned round through the whole 24 hours. On account of the annual motion of the sun among the stars, the *Solar Day*, by which

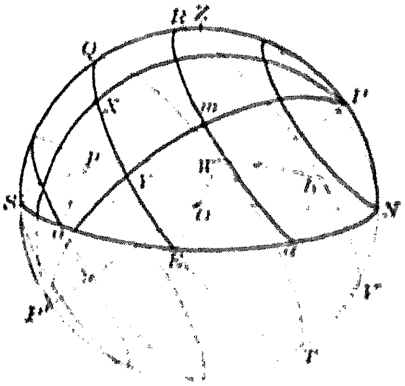

FIG. 5. Hour Circles, etc.

O, place of the Observer; *Z*, his Zenith.
SENW, the Horizon.
POP', the Axis of the Celestial Sphere.
P and *P'*, the two Poles of the Heavens.
EQWT, the Celestial Equator, or Equinoctial.
X, the Vernal Equinox, or "First of Aries."
PXP', the Equinoctial Colure, or Zero Hour Circle.
m, some Star.
Vm, the Star's *Declination*; *Pm*, its North-polar Distance.
Angle *mPH* = arc *QT*, the Star's (easterly) *Hour Angle* = 24h minus Star's (westerly) Hour Angle.
Angle *XPm* = arc *XT*, Star's *Right Ascension* = Sidereal time at the moment − 24h minus angle *XPQ*.

time is reckoned for ordinary purposes, is about 4 minutes longer than the sidereal day. The exact difference is $3^m 56^s.556$ (sidereal), or just one day in a year; there being 366¼ *sidereal* days in the year, as against 365¼ *solar* days. See also Arts. 110 and 1000.

27. Observatory Definition of Right Ascension. It is evident from the above definition of sidereal time that we may also define the Right Ascension of a star as *the sidereal time when the star crosses the meridian.* The Star and the Vernal Equinox are (practically)

fixed points in the sky, and do not change their relative position during the sky's apparent daily revolution; a given star, therefore, always comes to the meridian of any observer the same number of hours after the vernal equinox has passed; and this number of hours is the sidereal time at the moment of the star's transit, and measures its right ascension. In the observatory, this definition of right ascension is the most natural and convenient.

It is obvious that the right ascension of a star corresponds in the sky exactly with the *longitude* of a place on the earth, terrestrial longitude being reckoned from Greenwich, just as right ascension is reckoned from the vernal equinox.

N.B. *We shall find hereafter that the heavenly bodies have latitudes and longitudes of their own; but unfortunately these celestial latitudes and longitudes do not correspond to the terrestrial, and great care is necessary to prevent confusion.* (See Art. 179.)

28. An *armillary sphere*, or some equivalent apparatus, is almost essential to enable a beginner to get correct ideas of the points, circles, and co-ordinates defined above, but the figures will perhaps be of assistance.

The first of them (Fig. 4) represents the horizon, meridian, and prime vertical, and shows how the position of a star is indicated by its altitude and azimuth. This framework of circles, depending upon the direction of gravity, to an observer at any given station always remains *apparently* unchanged in position, while the sky apparently turns around outside it.

The other figure (Fig. 5) represents the system of points and circles which depend upon the earth's rotation, and are independent of the direction of gravity. The vernal equinox and the hour-circles apparently revolve with the stars while the pole remains fixed upon the meridian, and the equator and parallels of declination, revolving truly in their own planes, also appear to be at rest in the sky. But the whole system of lines and points represented in the figure (horizon and meridian alone excepted) may be considered as attached to, or marked out upon, the inner surface of the celestial vault and whirling with it.

It need hardly be said that the "appearances are deceitful" — that which is really carried around by the earth's rotation is the observer, with his plumb-line and zenith, his horizon and meridian; while the stars stand still — at least, their motions in a day are insensible as seen from the earth.

At the poles of the earth, which are, mathematically speaking, "singular" points, the definitions of the Meridian, of North and South, etc., break down.

There the pole (celestial) and zenith coincide, and any number of circles may be drawn through the two points, which have now become one. The horizon and equator coalesce, and the only direction on the earth's surface is due south (or north) — east and west have vanished.

A single step of the observer will, however, remedy the confusion: zenith and pole will separate, and his meridian will again become determinate.

29. To recapitulate: The *direction of gravity* at the point where the observer stands determines the Zenith and Nadir, the Horizon, and the Almucantars (parallel to the Horizon), and all the vertical circles. One of the verticals, the *Meridian*, is singled out from the rest by the circumstance that it passes through the *pole* of the sky, marking the North and South Points where it cuts the horizon.

Altitude and Azimuth (or their complements, Zenith Distance and Amplitude) are the co-ordinates which designate the position of a body by reference to the Zenith and the Meridian.

Similarly, the *direction of the earth's axis* (which is independent of the observer's place on the earth) determines the Poles, the Equator, the Parallels of Declination, and the Hour-Circles. *Two* of these Hour-Circles are singled out as reference lines; one of them, the Meridian, which passes through the Zenith, and is a purely *local* reference line; the other, the Equinoctial Colure, which passes through the Vernal Equinox, a point chosen from its relation to the sun's annual motion. Declination and *Hour-Angle* are the co-ordinates which refer the place of a star to the Pole and the Meridian; while Declination and *Right Ascension* refer it to the Pole and Equinoctial Colure. The latter are the co-ordinates usually employed in star-catalogues and ephemerides to define the positions of stars and planets, and correspond to Latitude and Longitude on the earth.

30. Relation of the Apparent Diurnal Motion of the Sky to the Observer's Latitude. — Evidently the apparent motions of the stars will be considerably influenced by the station of the observer, since the place of the pole in the sky will depend upon it. The *Altitude* of the pole, or its *height in degrees above* the horizon, is always equal to the *Latitude* of the observer. Indeed, the German word for latitude (astronomical) is *Polhöhe; i.e.*, simply "Pole-height."

This will be clear from Fig. 6. The latitude of a place is the *angle between its plumb-line and the plane of the equator*: the angle ONQ in the figure. [If the earth were truly spherical, N would coincide with C, the centre of the earth. The ordinary definition of latitude given in the geographies disregards the slight difference.]

Now the angle $H'OP'''$ is equal to ONQ, because their sides are mutually perpendicular; and it is also the *altitude of the pole*, because the line HH' is horizontal at O, and OP''', being directed towards the celestial pole, is therefore parallel to pCP'', the axis of the earth.

This fundamental relation, *that the altitude of the celestial pole is the Latitude of the observer*, cannot be too strongly impressed on the student's mind. The usual symbol for the latitude of a place is ϕ.

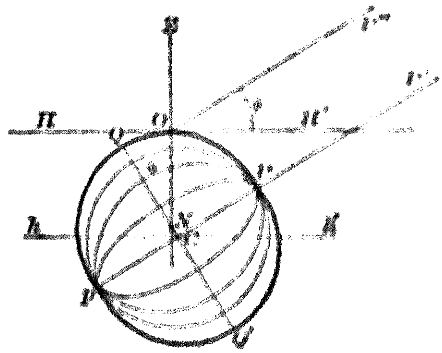

Fig. 6. — Relation of Latitude to the Elevation of the Pole.

31. The Right Sphere. — If the observer is situated at the earth's equator, *i.e.*, in latitude zero ($\phi = 0$), the pole will be in the horizon, and the equator will pass vertically overhead through the zenith.

The stars will rise and set vertically, and their diurnal circles will all be bisected by the horizon, so that they will be 12 hours above it and 12 below. This aspect of the heavens is called the *Right Sphere*.

32. The Parallel Sphere. — If the observer is at the pole of the earth ($\phi = 90°$), then the celestial pole will be in the zenith, and the equator will coincide with the horizon. If he is at the *North* Pole, all stars north of the celestial equator will remain permanently

equator, they will be half the time above the horizon and half the time below it. The moon would be visible for about a fortnight at a time, and the sun for six months.

33. The Oblique Sphere (Fig. 7).—At any station between the pole and equator the stars will move in circles oblique to the horizon, *SENW* in the figure. Those whose distance from the elevated pole is less than the latitude of the place will, of course, never sink below the horizon,—the radius of the "*Circle of Perpetual Apparition,*"

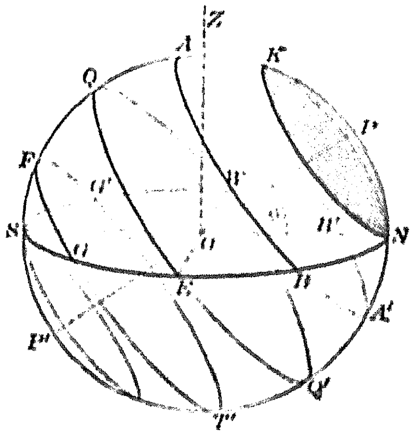

FIG. 7.—The Oblique Sphere and Diurnal Circles.

as it is called (the shaded cap around *P* in the figure), being just equal to the height of the pole, and becoming larger as the latitude increases. On the other hand, stars within the same distance of the depressed pole will lie within the "*Circle of Perpetual Occultation,*" and will never rise above the horizon.

A star exactly on the celestial equator will have its diurnal circle $EQWQ'$ bisected by the horizon, and will be above the horizon just as long as below it. A star north of the equator (if the North Pole is the elevated one) will have more than half of its diurnal circle above the horizon, and will be visible more than half the time; as, for instance, a star at A: and of course the reverse will be true of stars

on the other side of the equator.[1] Whenever the sun is north of the equator, the day will therefore be longer than the night for all stations in northern latitude: how much longer will depend both on the latitude of the place and the sun's distance from the celestial equator.

[1] A Celestial Globe will be of great assistance in studying these diurnal circles. The north pole of the globe must be elevated to an angle equal to the latitude of the observer, which can be done by means of the degrees marked on the brass meridian. It will then at once be easily seen what stars never set, which ones never rise, and during what part of the 24 hours any heavenly body at a known distance from the equator is above or below the horizon.

Note to Art. 6.

The ordinary estimate of the apparent size of the sun and moon as "about a foot in diameter" probably rests upon a physiological fact, viz., that in judging moderate distances, where we are not helped by intervening objects, we have to depend upon the muscular sensation of strain in converging our eyes towards the object looked at. For distances not exceeding fifty or sixty feet this is fairly accurate, but for distances above a hundred feet it entirely fails. When, therefore, we look at the moon in mid-heaven, our eyes directly inform us that it is at least a hundred feet away; on the other hand, from the absence of intervening objects we instinctively estimate the distance as the least possible consistent with the non-convergence of our eyes, and accordingly imagine the size of the disc to be about that of a ball which at a distance of a hundred feet or so would subtend the same angle of half a degree; i.e., about a foot.

CHAPTER II.

ASTRONOMICAL INSTRUMENTS.

34. ASTRONOMICAL observations are of various kinds: sometimes we desire to ascertain the apparent distance between two bodies at a given time; sometimes the position which a body occupies at a given time, or the moment it arrives at a given circle of the sky, usually the meridian. Sometimes we wish merely to examine its surface, to measure its light, or to investigate its spectrum; and for all these purposes special instruments have been devised.

We propose in this chapter to describe very briefly a few of the most important.

35. Telescopes in General.—Telescopes are of two kinds, refracting and reflecting. The former were first invented, and are much more used, but the largest instruments ever made are reflectors. In both the fundamental principle is the same. The large lens, or mirror, of the instrument forms at its focus a *real image* of the object looked at, and this image is then examined and magnified by the eye-piece, which in principle is only a magnifying-glass.

In the form of telescope, however, introduced by Galileo,[1] and still used as the "opera-glass," the rays from the object-glass are intercepted by a concave lens which performs the office of an eye-piece *before* they meet at the focus to form the "real image." But on account of the smallness of the field of view, and other objections, this form of telescope is never used when any considerable power is needed.

[1] In strictness, Galileo did not invent the telescope. Its *first* invention seems to have been in 1608, by Lipperhey, a spectacle-maker of Middleburg, in Holland; though the honor has also been claimed for two or three other Dutch opticians. Galileo, in his "Nuncius Sydereus," published in March, 1610, himself says that he had heard of the Dutch instruments in 1609, and by so hearing was led to construct his own, which, however, far excelled in power any that had been made previously; and he was the first to apply the telescope to Astronomy. See Grant's "History of Astronomy," pp. 514 and seqq.

36. Simple Refracting Telescope. — This consists essentially as shown in the figure (Fig. 8), of a tube containing two lenses: a single convex lens, A, called the object-glass; and another, of smaller size and short focus, B, called the eye-piece. Recalling the principles of lenses the student will see that if the instrument be directed at a distant object, the moon, for instance, all the rays, $a_0a_1a_2$, which fall upon the object-glass from a point at the *top* of the moon, will be collected at a in the focal plane, at the *bottom* of the image. Similarly rays from the *bottom* of the moon will go to b at the *top* of the image; moreover, since the rays that pass through the optical centre of the lens, o, are undeviated,[1] the angle a_0ob_0 will equal boa; or, in other words, if the focal length of the lens be five feet, for instance, then the image of the moon, seen from a distance of five feet, will appear just as large as the moon itself does in the sky, — it will subtend the same angle. If we look at it from a smaller distance,

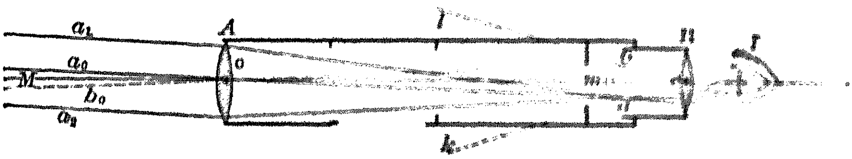

FIG. 8. — Path of the Rays in the Astronomical Telescope.

say from a distance of one foot, the image will look larger than the moon; and in fact, without using an eye-piece at all, a person with normal eyes can obtain considerable magnifying power from the object-glass of a large telescope. With a lens of ten feet focal length, such as is ordinarily used in an 8-inch telescope, one can easily see the mountains on the moon and the satellites of Jupiter, by taking out the eye-piece, and putting the eye in the line of vision some eight or ten inches back of the eye-piece hole.

The image is a *real* one; *i.e.*, the rays that come from different points in the object *actually meet* at corresponding points in the image, so that if a photographic plate were inserted at ab, and properly exposed, a picture would be obtained.

If we look at the image with the naked eye, we cannot come nearer

[1] In this explanation, we use the approximate theory of lenses (in which their thickness is neglected), as given in the elementary text-books. The more exact theory of Gauss and later writers would require some slight modifications in our statements, but none of any material importance. For a thorough discussion, see Jamin, "*Traité de Physique*," or Encyc. Britannica, — Optics.

rays from any point of the image will, after passing the lens, be converted into a parallel beam, and will appear to the eye to come from a point at an infinite distance, as if from an object in the sky. The rays which came from the top of the moon, for instance, and are collected at a in the image, will reach the eye as a beam *parallel to the line ae, which connects a with the optical centre of the eye-piece.* Similarly with the rays which meet at b. The observer, therefore, will see the *top* of the moon's disc in the direction ek, and the *bottom* in the direction el. It will appear to him *inverted*, and greatly magnified; its apparent diameter, as seen by the naked eye and measured by the angle aob (or its equal b_0oa_0), having been increased to aeb. Since both these angles are subtended by the same line ab, and are *small* (the figure, of course, is much out of proportion), they must be inversely proportional to the distance ob and eb; *i.e.*, $boa : bea = eb : ob$; or, putting this into words: The ratio between the natural apparent diameter of the object, and its diameter as seen through the telescope, *is equal to the ratio between the focal lengths of the eye-lens and object-glass.* This ratio is called the *magnifying power* of the telescope, and is therefore given by the simple formula $M = \frac{F}{f}$, where F is the focal length of the object-glass and f that of eye-piece,[1] while M is the magnifying power.

If, for example, the object-glass have a focal length of thirty feet, and the eye-piece of one inch, the magnifying power will be 360; the power may be changed at pleasure by substituting different eye-pieces, of which every large telescope has an extensive stock.

38. Brightness of Image.—Since all the rays from a star which fall upon the large object-glass are transmitted to the observer's eye (neglecting the losses by absorption and reflection), he obviously re-

[1] A magnifying power of 1 is no magnifying power at all. Object and image subtend equal angles. A magnifying power denoted by a fraction, say $\frac{1}{2}$, would be a *minifying* power, making the object look *smaller*, as when we look at an object through the wrong end of a spy-glass.

ceives a quantity of light much greater than he would naturally get: as many times greater as the area of the object-lens is greater than that of the pupil of the eye. If we estimate this latter as having a diameter of one-fifth of an inch, then a 1-inch telescope would increase the light twenty-five times, a 10-inch instrument 2500 times, and the great Lick telescope, of thirty-six inches' aperture, 32,400 times, the amount being proportional to the *square* of the diameter of the lens.

It must not be supposed, however, that the apparent brightness of an object like the moon, or a planet which shows a disc, is increased in any such ratio, since the eye-piece spreads out the light to cover a vastly more extensive angular area, according to its magnifying power; in fact, it can be shown that no optical arrangement can show an *extended surface* brighter than it appears to the naked eye. But the *total quantity* of light utilized is greatly increased by the telescope, and in consequence, multitudes of stars, far too faint to be visible to the unassisted eye, are revealed, and, what is practically very important, *the brighter stars are easily seen by day* with the telescope.

39. Distinctness of Image. — This depends upon the exactness with which the lens gathers to a single *point* in the focal image all the rays which emanate from the corresponding point in the object. A single lens, with spherical surfaces, cannot do this very perfectly, the "aberrations" being of two kinds, the *spherical* aberration and the *chromatic*. The former could be corrected, if it were worth while, by slightly modifying the form of the lens-surfaces; but the latter, which is far more troublesome, cannot be cured in any such way. The violet rays are more refrangible than the red, and come to a focus nearer the lens; so that the image of a star formed by such a lens can never be a luminous point, but is a round patch of light of different color at centre and edge.

40. Long Telescopes. — By making the diameter of the lens very small as compared with its focal length, the aberration becomes less conspicuous; and refractors were used, about 1680, having a length of more than 100 feet and a diameter of five or six inches. The object-glass was mounted at the top of a high pole and the eye-piece was on a separate stand below. Huyghens and Cassini both used such "aerial telescopes," and one of Huyghens' object-glasses, of six inches aperture and 123 feet focus, is still preserved in the Museum of the Royal Society in London.

41. The Achromatic Telescope. — The chromatic aberration of a lens, as has been said, cannot be cured by any modification of the lens itself; but it was discovered in England about 1760 that it can be nearly corrected by making the object-glass of *two* (or more) lenses, of *different kinds of glass*, one of the lenses being convex and the other concave. The convex lens is usually made of *crown* glass, the concave of *flint* glass. At the same time, by properly choosing the curves, the *spherical* aberration can also be destroyed, so that such a compound object-glass comes reasonably near to fulfilling the condition, that it should gather to a mathematical point in the image all the rays that reach the object-glass from a single point in the object.

These object-glasses admit of a considerable variety of forms. Formerly they were generally made, as in Fig. 9, No. 3, having the two lenses close together, and the adjacent surfaces of the same, or nearly the same, curvature. In small object-glasses the lenses are often cemented together with Canada balsam or some other transparent medium. At present some of the best makers separate the two lenses by a considerable distance, so as to admit a free circulation of air between them; in the Pulkowa and Princeton object-glasses, constructed by Clark, the lenses are seven inches apart, and in the Lick telescope six and a half inches; as in No. 1. In a form devised by Gauss (No. 2), which has some advantages, but is difficult of construction, the curves are very deep, and both the lenses are of watch-glass form — concave on one side and convex on the other. In all these forms the crown glass is outside; Steinheil, Hastings, and others have constructed lenses with the *flint glass* lens outside. Object-glasses are sometimes made with *three* lenses instead of two; a slightly better correction of aberrations can be obtained in this way, but the gain is too small to pay for the extra expense and loss of light.

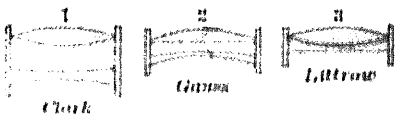

Fig. 9. — Different Forms of the Achromatic Object-glass.

42. Secondary Spectrum. — It is not, however, possible with the kinds of glass ordinarily employed to secure a perfect correction of the color. Our best achromatic lenses bring the yellowish green rays to a focus *nearer the lens* than they do the red and violet. In consequence, the image of a bright star is surrounded by a purple halo, which is not very noticeable in a good telescope of small size, but is very conspicuous and troublesome in a large instrument.

This imperfection of achromatism makes it unsatisfactory to use an ordinary lens (*visually* corrected) for astronomical photography. To fit it to make good photographs, it must either be specially corrected for the rays

that are most effective in photography, the blue and violet (in which case it will be almost worthless visually), or else a subsidiary lens, known as a "photographic corrector," may be provided, which can be put on in front of the object-glass when needed. A new form of object-glass, devised independently by Pickering in this country and Stokes in England, avoids the necessity of a third lens by making the crown-glass lens of such a form that when put close to the flint lens, with the *flatter side out*, it makes a perfect object-glass for visual purposes; but by simply reversing the crown lens, with the more convex side outward, and separating the lenses an inch or two, it becomes a photographic object-glass.

42*. Photo-visual Objectives. Much is hoped from the new kinds of glass now made at Jena, but there has been great difficulty in producing discs satisfactorily homogeneous, of such chemical composition that the surface will not "rust," and large enough for telescopes of any size. Since 1894, however, the English opticians, Cooke & Sons, have been advertising "perfectly achromatic" triple object-glasses, which are asserted to be equally perfect for visual and photographic use. They offer to make lenses twenty inches in diameter, but up to 1898 had produced only a few as large as six or eight inches, which have been examined and very favorably reported on by eminent astronomers. Possibly the new century will open a new era in telescope-making.

43. Diffraction and Spurious Disc. — Even if a lens were perfect as regards the correction of aberrations, the "wave" nature of light prevents the image of a luminous point from being also a point; the image must *necessarily* consist of a central *disc*, brightest in the centre and fading to darkness at the edge, and this is surrounded by a series of bright rings, of which, however, only the smallest one is generally easily seen. The size of this disc-and-ring system can be calculated from the known wave-lengths of light and the dimensions of the lens, and the results agree very precisely with observation. The diameter of the "spurious disc" *varies inversely* with the aperture of the telescope. According to Dawes, it is about 4".5 for a 1-inch telescope: and consequently 1" for a 4½-inch instrument, 0".5
so on.

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perfectly round and well defined, without wings or tails of any kind, having around it from one to three bright rings, separated by distances somewhat greater than the diameter of the disc. If, however, the magnifying power is more than about 50 to the inch of aperture, the edge of the disc will begin to appear hazy. There is seldom any advantage in the use of a magnifying power exceeding 75 to the inch, and for most purposes powers ranging from 20 to 40 to the inch are most satisfactory.

44. Eye-Pieces.—For many purposes, as for instance the examination of close double stars, there is no better eye-piece than the simple convex lens; but it performs well only when the object is exactly in the centre of the field. Usually it is best to employ for the *eye-piece* a combination of two or more lenses.

Eye-pieces belong to two classes, the *positive* and the *negative*. The former, which are much more generally useful, act as simple magnifying-glasses, and can be used as hand magnifiers if desired. The focal image formed by the object-glass lies *outside* of the eye-piece.

In the *negative* eye-pieces, on the other hand, the rays from the object-glass are intercepted before they come to the focus, and the image is formed between the lenses of the eye-piece. Such an eye-piece cannot be used as a hand magnifier.

45. The simplest and most common forms of these eye-pieces are the Ramsden (positive) and Huyghenian (negative). Each is composed of two plano-convex lenses, but the arrangement and curves differ, as shown in Fig. 10. The former gives a very flat field of view, but is not achromatic; the latter is more nearly achromatic, and possibly defines a little better just at the centre of the field; but the fact that it is a *negative* eye-piece greatly restricts its usefulness. In the Ramsden eye-piece the focal lengths of the two component lenses, both of which have their flat sides out, are about equal to each other, and their distance is about one-third of the sum of the focal lengths. In the Huyghenian the curved sides of the lenses are both turned towards the object-glass; the focal distance of the field lens should be exactly *three* times that of the lens next the eye, and the distance between the lenses one-half the sum of the focal lengths.

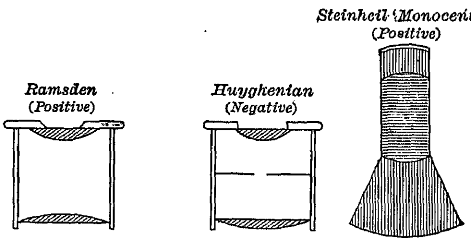

FIG. 10.—Various Forms of Telescope Eye-piece.

There are numerous other forms of eye-piece, each with its own advantages and disadvantages. The *erecting* eye-piece, used in spy-glasses, is

essentially a compound microscope, and gives erect vision by again inverting the already inverted image formed by the object-glass.

It is obvious that in a telescope of any size the object-glass is the most important and expensive part of the instrument. Its cost varies from a few hundred dollars to many thousands, while the eye-pieces generally cost only from $5 to $20 apiece.

46. Reticle. — When a telescope is used for *pointing*, as in most astronomical instruments, it must be provided with a *reticle* of some sort. This is usually a metallic frame with *spider lines* stretched across it, placed, not near the object-glass itself (as is often supposed), but at the *focus* of the object-glass, where the image is formed, as at *a b* in Fig. 8.

It is usually so arranged that it can be moved in or out a little to get it exactly into the focal plane, and then, when the eye-piece (positive) is adjusted for the observer's eye to give distinct vision of the object, the "wires," as they are called, will also be equally distinct. As spider-threads are very fragile, and likely to get broken and displaced, it is often better to substitute filaments of *quartz*, or a thin plate of glass with lines ruled upon it and blackened. The field of view, or the threads themselves, must be illuminated in order to make them visible in darkness.

47. The Reflecting Telescope. — When the chromatic aberration of lenses came to be understood through the optical discovery of the dispersion of light by Newton, the reflecting telescope was invented, and held its place as the instrument for star-gazing until well into the present century, when large achromatics began to be made. There are several varieties of reflecting telescope, all agreeing in the substitution of a large concave mirror in place of the object-glass of the refractor, but differing in the way in which they get at the image formed by this mirror at its focus in order to examine it with the eye-piece.

48. In the Herschelian form, which is the simplest, but only suited to very large instruments, the mirror is *tipped* a little, so as to throw the image to the side of the tube, and the observer stands with his back to the object and looks down into the tube. If the telescope is as much as two or three feet in diameter, his head will not intercept enough light to do much harm, — not nearly so much as would be lost by the second reflection necessary in the other forms of the instrument. But the inclination of the mirror, and the heat from the observer's person, are fatal to any very accurate definition, and unfit this form of instrument for anything but the observation of nebulæ and objects which mainly require light-gathering power.

the focus of the large mirror, which makes the instrument a little shorter, and gives a flatter field of view.

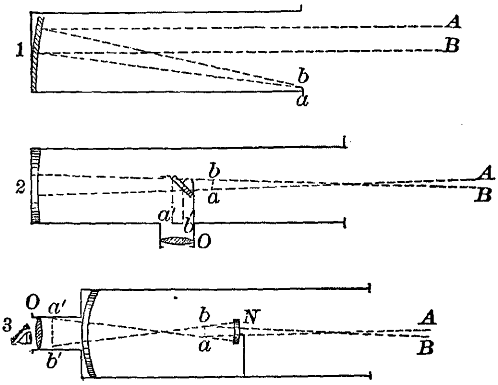

FIG. 11. — Different Forms of Reflecting Telescope.
1. The Herschelian; 2. The Newtonian; 3. The Gregorian.

Formerly the great mirror was always made of a composition of copper and tin (two parts of copper to one of tin) known as "speculum metal." At present it is usually made of glass *silvered* on the front surface, by a chemical process which deposits the metal in a thin, brilliant film. These silver-on-glass reflectors, when new, reflect much more light than the old specula, but the film does not retain its polish so long. It is, however, a comparatively simple matter to renew the film when necessary.

The largest telescopes ever made have been reflectors. At the head of the list stands the enormous instrument of Lord Rosse, constructed in 1842, with a mirror six feet in diameter and sixty feet focal length. Next in order comes the five-foot silver-on-glass reflector of Mr. Common[1] (1889), and another of the same size, figured by Mr. Ritchey, and recently mounted at the Mount Wilson Solar Observatory, near Pasadena, California. Then there are several instruments of four feet aperture, first among which is the great telescope of the elder Herschel, built in 1789.

49. Relative Advantages of Refractors and Reflectors. — There has been a good deal of discussion on this point, and each construction has its partisans.

In favor of the reflectors we may mention, —

First. *Ease of construction and consequent cheapness.* The concave mirror

[1] Acquired and mounted by Harvard College Observatory in 1905.

has but one surface to figure and polish, while an object-glass has four. Moreover, as the light goes through an object-glass, it is evident that the glass employed must be perfectly clear and of uniform density through and through; while in the case of the mirror, the light does not penetrate the material at all. This makes it vastly easier to get the material for a large mirror than for a large lens.

Second (and immediately connected with the preceding). *The possibility of making reflectors much larger than refractors.* Lord Rosse's great reflector is six feet in diameter, while the Yerkes telescope, the largest refractor in use, is only forty inches. (Its focal length, however, is sixty-five feet.)

Third. *Perfect achromatism.* This is unquestionably a very great advantage, especially in photographic and spectroscopic work.

But, on the whole, the advantages are generally considered to be with the refractors.

In their favor we mention

First. *Great superiority in light.* No mirror (unless, perhaps, a *freshly polished* silver-on-glass film) reflects much more than three-quarters of the incident light; while a good (single) lens transmits over 90 per cent. In a good refractor about 80 per cent of the light reaches the eye, after passing through the four lenses of the object-glass and eyepiece. In a Newtonian reflector, in average condition, the percentage seldom exceeds 50 per cent, and more frequently is lower than higher.

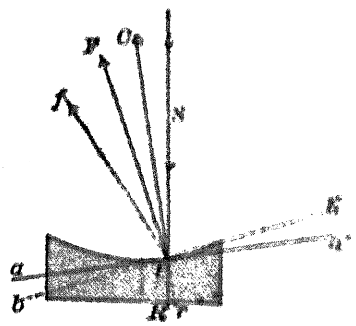

FIG. 12. — Effect of Surface Errors in a Mirror and in a Lens.

Second. *Better definition.* — Any slight error at a point in the surface of a glass lens, whether caused by faulty workmanship or by distortion, affects the direction of the ray passing through it only *one-third* as much as the same error on the surface of a mirror would do.

If, for instance, in Fig. 12, an element of the surface at P is turned out of its proper direction, aa', by a small angle, so as to take the direction bb', then the *reflected* ray will be sent to f, and its deviation will be twice the angle aPb. But since the index of refraction of glass is about 1.5 the change in the direction of the *refracted* ray from R to r will only be about *two-thirds* of aPb.

Moreover, so far as distortions are concerned, when a lens bends a little by its own weight, *both sides are affected in a nearly compensatory manner*, while in a mirror there is no such compensation. As a consequence, mirrors very seldom indeed give any such definition as lenses do. The least fault of workmanship, the least distortion by their own weight, the slightest difference of temperature, between front and back, will absolutely ruin the image, while a lens would be but slightly affected in its performance by the same circumstances.

and Chronograph. — Modern practical astronomy owes its develop-ment as much to the clock and chronometer as to the telescope. The ancients possessed no accurate instruments for the measurement of time, and until within 200 years, the only reasonably precise method of fixing the time of an important observation, as, for instance, of an eclipse, was by noting the *altitude* of the sun, or of some known star at or very near the moment.

It is true that the Arabian astronomer Ibn Jounis had made some use of the pendulum about the year 1000 A.D., more than 500 years before Galileo introduced it to Europeans. But it was not until nearly a century after Galileo's discovery that Huyghens applied it to the construction of clocks (in 1657).

So far as the principles of construction are concerned, there is no difference between an astronomical clock and any other. As a matter of convenience, however, the astronomical clock is almost invariably made to beat seconds (rarely half-seconds), and has a conspicuous second-hand, while the hour-hand makes but *one* revolution a day, instead of two, as usual, and the face is marked for twenty-four hours instead of twelve. Of course it is constructed with extreme care in all respects.

The Escapement, or "*Scapement*," is often of the form known as the "Graham Dead-beat"; but it is also frequently one of the numerous "gravity" escapements which have been invented by ingenious mechanicians. The office of the escapement is to be "unlocked" by the pendulum at each vibration, so as to permit the wheel-work to advance one step, marking a second (or sometimes two seconds), upon the clock-face; while, at the same time, the escapement gives the pendulum a slight impulse, just equal to the resistance it has suffered in performing the unlocking. The work done by the pendulum in "unlocking" the train, *and the corresponding impulse, ought to be perfectly constant*, in spite of all changes in the condition of the train of wheels; and it is *desirable*, though not *essential*, that this work should be as *small* as possible.

51. The pendulum itself is usually suspended by a flat spring, and great pains should be taken to have the support extremely firm: this is often neglected, and the clock then cannot perform well.

Compensation for Temperature. — In order to keep perfect time, the pendulum must be a "compensation pendulum"; *i.e.*, constructed in such a way that changes of temperature will not change its length.

An uncompensated pendulum, with steel rod, changes its daily rate about one-third of a second for each degree of temperature (centigrade). A wooden pendulum rod is much less affected by temperature, but is very apt to be disturbed by changes of *moisture*.

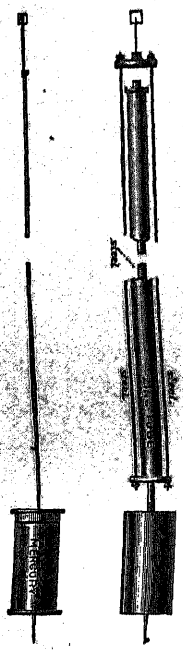

FIG. 13.
Compensation Pendulums.
1. Graham's Pendulum.
2. Zinc-Steel Pendulum.

Graham's mercurial pendulum (Fig. 13) is the one most commonly used. It consists simply of a jar (usually steel), three or four inches in diameter, and about eight inches high, containing forty or fifty pounds of mercury, and suspended at the end of a steel rod. When the temperature rises, the rod lengthens (which would make the clock go slower); but, at the same time, the mercury expands, from the bottom upwards, just enough to compensate. This pendulum will perform well only when not exposed to *rapid changes* of temperature. Under rapid changes the compensation *lags*. If, for instance, it grows warm quickly, the rod will expand before the mercury does; so that, *while the mercury is growing warmer*, the clock will run slow, though after it has become warm the rate may be all right.

A compensation pendulum, constructed on the principle of the old gridiron pendulum of Harrison, but of zinc and steel instead of brass and steel, is now much used. The compensation is not so easily adjusted as in the mercurial pendulum, but when properly made the mechanism acts well, and bears rapid alterations of temperature much better than the mercurial pendulum. The heavy pendulum-bob, a lead cylinder, is hung at the end of a steel rod, which is suspended from the top of a zinc tube, and hangs through the centre of it. This tube is itself supported *at the bottom* by three or four steel rods which hang from a piece attached to the pendulum spring. The standard clock at Greenwich has a pendulum of this kind.

52. **Effect of Atmospheric Pressure.** — In consequence of the buoyancy of the air, and its resistance to motion, a pendulum swings

a little more slowly than it would *in vacuo*, and every change in the density of the air affects its rate more or less. With mercurial pendulums, of ordinary construction, the "*barometric coefficient*," as it is called, is about one-third of a second for an inch of the barometer; *i.e.*, an increase of atmospheric density which would raise the barometer one inch would make the clock *lose* about one-third of a second daily. It varies considerably, however, with different pendulums.

It is not very usual to take any notice of this slight disturbance; but when the extremest accuracy of time-keeping is aimed at, the clock is either sealed in an air-tight case from which the air is partially exhausted (as at Berlin), or else some special mechanism, controlled by a barometer, is devised to compensate for the barometric changes, as at Greenwich. In the Greenwich clock a magnet is raised or lowered by the rise or fall of the mercury in a barometer attached to the clock-case. When the magnet rises, it approaches a bit of iron two or three inches above it, fixed to the bottom of the pendulum, and the increase of attraction accelerates the rate just enough to balance the retardation due to the air's increased density and viscosity. There are several other contrivances for the same purpose.

53. Error and Rate. — The "*error*," or "*correction*" of a clock is the amount that *must be added* to the indication of the clock-face at any moment in order to give the *true time;* it is, therefore, *plus* (+) when the clock is *slow*, and *minus* (−) when it is *fast*. The *rate* of a clock is the amount of its *daily gain or loss; plus* (+) when the clock is *losing*. Sometimes the *hourly rate* is used, but "*hourly*" is then always specified.

A *perfect* clock is one that has a *constant rate*, whether that rate be large or small. It is desirable, for convenience' sake, that both error and rate should be small; but this is a mere matter of adjustment by the user of the clock, who adjusts the error by setting the hands, and the rate by raising or lowering the pendulum-bob.

The final adjustment of rate is often obtained by first setting the pendulum-bob so that the clock will run slow a second or two daily, and then putting on the top of the bob little weights of a gramme or two, which will accelerate the motion. They can be dropped into place or knocked off without stopping the clock or perceptibly disturbing it.

The very best clocks will run three or four years without being stopped for cleaning, and will retain their rate without a change of more than one-fifth of a second, one way or the other, during the whole time. But this is